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Magnetic field measurements of O stars with FORS 1 at the VLT*

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ABSTRACT

Context. The presence of magnetic fields in O-type stars has been suspected for a long time. The discovery of such fields would explain a wide range of well documented enigmatic phenomena in massive stars, in particular cyclical wind variability, Hα emission variations, chemical peculiarity, narrow X-ray emission lines and non-thermal radio/X-ray emission.
Aims. To investigate the incidence of magnetic fields in O stars, we acquired 38 new spectropolarimetric observations with FORS 1 (FOcal Reducer low dispersion Spectrograph) mounted on the 8-m Kueyen telescope of the VLT.
Methods. Spectropolarimetric observations have been obtained at different phases for a sample of 13 O stars. 10 stars were observed in the spectral range 348–589 nm, HD 36879 and HD 148937 were observed in the spectral region 325–621 nm, and HD 155806 was observed in both settings. To prove the feasibility of the FORS 1 spectropolarimetric mode for the measurements of magnetic fields in hot stars, we present in addition 12 FORS 1 observations of the mean longitudinal magnetic field in θ^1 Ori C and compare them with measurements obtained with the MuSiCoS, ESPaDOnS and Narval spectropolarimeters.
Results. Most stars in our sample which have been observed on different nights show a change of the magnetic field polarity, but a field at a significance level of 3σ has been detected only in four stars, HD 36879, HD 148937, HD 152408, and HD 164794. The largest longitudinal magnetic field, $\langle B_z\rangle = -276\pm88$ G, was detected in the Of?p star HD 148937. We conclude that large-scale organised magnetic fields with polar field strengths larger than 1 kG are not widespread among O-type stars.

Key words. polarization - stars: early-type - stars: magnetic fields

1. Introduction

Massive stars usually end their evolution with a final supernova explosion, producing neutron stars or black holes. The initial masses of these stars range from ∼9–10 $M_\odot$ to 100 $M_\odot$ or more, which correspond to spectral types earlier than about B2. Magnetic O stars with masses larger than 30 $M_\odot$ and their WR descendants have been suggested as progenitors of magnetars (Gaensler et al. 2005). Contrary to the case of Sun-like stars, the magnetic fields of stars on the upper main sequence (Ap/Bp stars), white dwarfs, and neutron stars are dominated by large spatial scales and do not change on yearly time scales. In each of these classes there is a wide distribution of magnetic field strengths, but the distribution of magnetic fluxes appears to be similar in each class, with maxima of $\Phi_{\max} = \pi R^2 B \sim 10^{27-28}$G cm^2 (Reisenegger 2001, Ferrario & Wickramasinghe 2005), arguing for a fossil field whose flux is conserved along the path of stellar evolution. Braithwaite & Spruit (2004) confirmed through simulations that there are stable MHD configurations that might account for long-lived, ordered fields in these types of stars.

However, very little is known about the existence, origin, and role of magnetic fields in massive O and Wolf-Rayet stars. The lack of information is especially disturbing because magnetic fields may have paramount influence on the stellar evolution of high-mass stars. Maeder & Meynet (2005) examined the effect of magnetic fields on the transport of angular momentum and chemical mixing, and they found that the potential influence on the evolution of massive stars is dramatic.

Indirect observational evidence for the presence of magnetic fields are the many unexplained phenomena observed in massive stars, that are thought to be related to magnetic fields. One of the main indications that massive stars have magnetic fields is the cyclic behaviour on a rotational timescale observed in the UV wind lines (e.g. Henrichs et al. 2005). Other indications are variability observed in the H and He lines (Moffat & Michaud 1981, Stahl et al. 1996, Rauw et al. 2001), narrow X-ray emission lines (Cohen et al. 2003, Gagné et al. 2005) and the presence of non-thermal radio emission (Bieging et al. 1989, Scuderi et al. 1998, Schnerr et al. 2007).

Direct measurements of the magnetic field strength in massive stars using spectropolarimetry to determine the Zeeman splitting of the spectral lines is difficult, as only fewer spectral lines are available for the measurements and

* Based on observations obtained at the European Southern Observatory, Paranal, Chile (ESO programmes 075.D-0432(A), 078.D-0330(A), 079.D-0241(A), 080.D-0383(A)).

Table 1. Target stars discussed in this paper. Spectral types are from Maíz-Apellániz et al. (2004), $v \sin i$ values are taken from Howarth et al. (1997). For two stars, HD 135240 and HD 167771, not considered by Howarth et al. (1997), the $v \sin i$ values are from the Bright Star Catalogue (Hoffleit & Jaschek 1991). The $v \sin i$ value for HD 148937 was recently reported by Nazé et al. (2008)

HD number	Other name	V	Spectral type	$v \sin i$ [km s^{-1}]
36879	BD+21 899	7.6	O7 V(n)	163
112244	HR 4908	5.3	O8.5 Iab(f)	147
135240	δ Cir	5.1	O7.5 III((f))	189
135591	HR 5680	5.3	O7.5 III((f))	78
148937	CD−47 10855	6.8	O6.5 f?p	45
151804	HR 6245	5.2	O8 Iaf	104
152408	HR 6272	5.9	O8: Iafpe	85
155806	HR 6397	5.6	O7.5 V[n]e	91
162978	63 Oph	6.2	O7.5 II((f))	86
164794	9 Sgr	5.9	O4 V((f))	70
167263	16 Sgr	6.0	O9.5 II-III((n))	99
167771	HR 6841	6.5	O7 III:(n)((f))	90
188001	9 Sge	6.2	O7.5 Iaf	93

which are usually strongly broadened by rapid rotation. So far a magnetic field has only been found in three O stars, θ^1 Ori C, HD 155806 and HD 191612 (Donati et al. 2002, Hubrig et al. 2007, Donati et al. 2006a) and in a handful of early B-type stars (Henrichs et al. 2000, Neiner et al. 2003a, Neiner et al. 2003b, Neiner et al. 2003c, Hubrig et al. 2006, Donati et al. 2006b, Hubrig et al. 2007). In this paper we present the results of the measurements of magnetic fields in 13 O type stars using FORS 1 at the VLT in spectropolarimetric mode. Our observations and the data reduction are described in Sect. 2, the obtained results in Sect. 3 and their discussion is presented in Sect. 4.

2. Observations and data reduction

The major part of the observations reported here have been carried out between March and August of 2005 in service mode at the European Southern Observatory with FORS 1 mounted on the 8-m Kueyen telescope of the VLT. This multi-mode instrument is equipped with polarisation analyzing optics comprising super-achromatic half-wave and quarter-wave phase retarder plates, and a Wollaston prism with a beam divergence of 22″ in standard resolution mode. 11 O-type stars have been observed in 2005 with the GRISM 600B in the wavelength range 3480–5890 Å to cover all hydrogen Balmer lines from Hβ to the Balmer jump. Their selection was based on the extensive study of wind variability in O and B stars using the IUE data archive by ten Kulve (2004), anomalous X-ray behaviour and brightness. The spectral types of the studied stars are listed in Table 1 and the observed FORS 1 spectra in integral light are presented in Fig. 1. The observation of HD 36879 has been obtained at the beginning of September 2007 and two more observations, one for the star HD 148937 and another one for the star HD 155806, have been obtained at the end of March 2008. These observations have been carried out with the GRISM 600B and a new mosaic detector with blue optimised E2V chips, which was implemented in FORS 1 at the beginning of April 2007. It has a pixel size of 15 μm (compared to 24 μm for the previous Tektronix chip) and higher efficiency in the wavelength range below 6000 Å. With the new mosaic detector and the grism 600B we are also able now to cover a much larger spectral range, from 3250 to 6215 Å.

12 observations of the magnetic O star θ^1 Ori C, distributed over the rotational period, have been obtained in 2006 with GRISM 600R in the wavelength range 5240–7380 Å. In all observations the narrowest slit width of 0.″4 was used to obtain a spectral resolving power of $R \sim 2000$ with GRISM 600B and $R \sim 3000$ with GRISM 600R.

The mean longitudinal magnetic field, $\langle B_z \rangle$, has been derived using

$$\frac{V}{I} = -\frac{g_{\rm eff} e \lambda^2}{4\pi m_e c^2}\,\frac{1}{I}\,\frac{{\rm d}I}{{\rm d}\lambda}\,\langle B_z\rangle\,, \qquad (1)$$

where V is the Stokes parameter which measures the circular polarisation, I is the intensity in the unpolarized spectrum, $g_{\rm eff}$ is the effective Landé factor, e is the electron charge, λ is the wavelength expressed in Å, m_e the electron mass, c the speed of light, ${\rm d}I/{\rm d}\lambda$ is the derivative of Stokes I, and $\langle B_z\rangle$ is the mean longitudinal field expressed in Gauss. To minimize the cross-talk effect we executed the sequence +45−45, +45−45, +45−45 etc. and calculated the values V/I using:

$$\frac{V}{I} = \frac{1}{2}\left\{\left(\frac{f^{\rm o}-f^{\rm e}}{f^{\rm o}+f^{\rm e}}\right)_{\alpha=-45^\circ} - \left(\frac{f^{\rm o}-f^{\rm e}}{f^{\rm o}+f^{\rm e}}\right)_{\alpha=+45^\circ}\right\}, \qquad (2)$$

where α gives the position angle of the retarder waveplate and $f^{\rm o}$ and $f^{\rm e}$ are ordinary and extraordinary beams, respectively. Stokes I values have been obtained from the sum of the ordinary and extraordinary beams. To derive $\langle B_z\rangle$, a least-squares technique has been used to minimize the expression

$$\chi^2 = \sum_i \frac{(y_i - \langle B_z\rangle\, x_i - b)^2}{\sigma_i^2} \qquad (3)$$

where, for each spectral point i, $y_i = (V/I)_i$, $x_i = -\frac{g_{\rm eff} e \lambda_i^2}{4\pi m_e c^2}\,(1/I \times {\rm d}I/{\rm d}\lambda)_i$ and b is a constant term that, assuming that Eq. 1 is correct, approximates the fraction of instrumental polarisation not removed after the application of Eq. 2 to the observations. During the commissioning of FORS 1, this instrumental polarisation term was found to be wavelength independent. A wavelength dependent instrumental polarisation would also be visible in the V/I spectra, but we do not see anything like this in the data. For each spectral point i, the derivative of Stokes I with respect to the wavelength was evaluated as

$$\left(\frac{{\rm d}I}{{\rm d}\lambda}\right)_{\lambda=\lambda_i} = \frac{N_{i+1}-N_{i-1}}{\lambda_{i+1}-\lambda_{i-1}}, \qquad (4)$$

where N_i is the photon count at wavelength λ_i. As noise strongly influences the derivative, we interpolate the data after spectrum extraction with splines. In our calculations we assumed a Landé factor $g_{\rm eff}$=1 for hydrogen lines. We are using 23 lines of He I, He II, C III, C IV, N II, N III, and O III in our analysis. The average Landé factor of these lines for measurements carried out with GRISM 600B is $g_{\rm eff}$=1.07 and the average Landé factor of these lines for measurements carried out with GRISM 600R is

$g_{\rm eff}$=1.02. More details of the observing technique are given by Bagnulo et al. (2002) and Hubrig et al. (2004a, 2004b).

Longitudinal magnetic fields were measured in two ways: using only the absorption hydrogen Balmer lines or using the whole spectrum including all available absorption lines of hydrogen, He I, He II, C III, C IV, N II, N III and O III. The lines that show evidence for emission were not used in the determination of the magnetic field strength (see Sec. 3). The feasibility of longitudinal magnetic field measurements in massive stars using FORS 1 in spectropolarimetric mode was demonstrated by recent studies of early B-type stars (e.g., Hubrig et al. 2006, Hubrig et al. 2007, Hubrig et al. 2008). In Fig. 2 we demonstrate the excellent potential of FORS 1 for measuring magnetic fields in the star θ^1 Ori C, which was the first O-type star with a detected weak magnetic field varying with the rotation period of 15.4 days. The open symbols represent previous magnetic field measurements by other authors. It is obvious that the FORS 1 measurements are sufficiently accurate, showing a smooth sinusoidal curve in spite of the phase gap between 0.60 and 0.88. The values for the measured longitudinal magnetic field in different rotational phases are presented in Table 2.

However, our observations determine a magnetic geometry different from the one deduced by Wade et al. (2006). The maxima and minima of the measured longitudinal field as well as the phases of the field extrema appear to be different. We are not aware of any systematic shift between FORS 1 measurements and measurements with other spectropolarimeters. We periodically observe well-studied magnetic stars with known variation curves and usually our measurements are in good agreement with those obtained with other instruments. On the other hand, the reason for such a shift is understandable since Wade et al. (2006) used for their measurements just three metal lines, O III 5592, C IV 5801, and C IV 5811. The profiles of these lines exhibit clear variations which could be signatures of an uneven distribution of these elements over the stellar surface (see e.g. Reiners et al. 2000). Such an uneven element distribution of metal lines will affect the line-of-sight component of the magnetic field integrated over the stellar surface. A different set of lines is of special relevance for magnetic field measurements only in the cases where few lines are used. If the distribution of spots of different elements on the stellar surface is related to the magnetic field geometry (as is usually found in classical magnetic Ap and Bp stars where certain elements are concentrated on magnetic poles and other elements along the stellar magnetic equator), magnetic field measurements using the lines of different elements will produce different magnetic field strengths, depending on the location of the elemental spots on the stellar surface. With FORS 1 we use for the measurements all absorption lines belonging to various chemical elements together, and in this way might sample the magnetic field more uniformly over the observed hemisphere.

Without further detailed high-resolution studies of polarized line profiles of different elements it is currently not obvious which set of measurements lies closer to the true longitudinal magnetic field of θ^1 Ori C. Assuming an inclination of the rotation axis to the line-of-sight of i=45° (Wade et al. 2006), our modeling of the longitudinal field variation constrains the dipole magnetic field geometry of θ^1 Ori C to $B_d \approx 1100$ G and β close to 90°, where B_d is the dipole intensity and β is the obliquity angle.

Table 2. Magnetic field measurements of θ^1 Ori C with FORS 1. Phases are calculated according to the ephemeris of Stahl et al. (1996), JD = 2 448 833.0 + 15.422 E. All quoted errors are 1σ uncertainties.

MJD	Phase	$\langle B_z \rangle$ [G]
54107.221	0.0257	240±59
54108.272	0.0939	341±90
54109.127	0.1494	267±81
54112.174	0.3469	78±72
54114.149	0.4750	−166±75
54116.057	0.5987	−353±75
54155.062	0.1279	293±69
54156.072	0.1933	293±48
54157.051	0.2569	189±47
54158.086	0.3239	97±57
54177.064	0.5545	−272±72
54182.048	0.8777	84±54

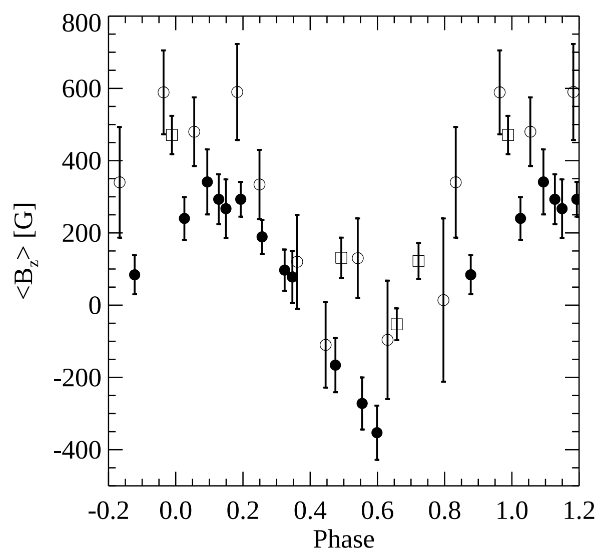

Fig. 2. $\langle B_z \rangle$ vs. the rotation phase for θ^1 Ori C. Open circles: Observations by Wade et al. (2006) with MuSiCoS. Open squares: Observations by Petit et al. (2008) with ESPaDOnS and Narval. Filled circles: Our FORS 1 measurements. For one measurement of θ^1 Ori C presented by Petit et al. (2008) the phase 0.05 seems to be erroneous. Using the HJD of the observations presented in their Table 1, we calculate the phase 0.99.

3. Results

Because of the strong dependence of the longitudinal magnetic field on the rotational aspect, its usefulness to characterise actual magnetic field strength distributions depends on the sampling of the various rotation phases, hence various aspects of the magnetic field. All targets were observed on three or four different nights. As mentioned before, the exceptions are the stars HD 36879 and HD 148937, which we have been able to observe only once. Apart from HD 148937 which has a rotation period of seven days (Nazé et al. 2008), no exact rotation periods are known for the other stars in our sample, and certainly, it is not possible to characterise

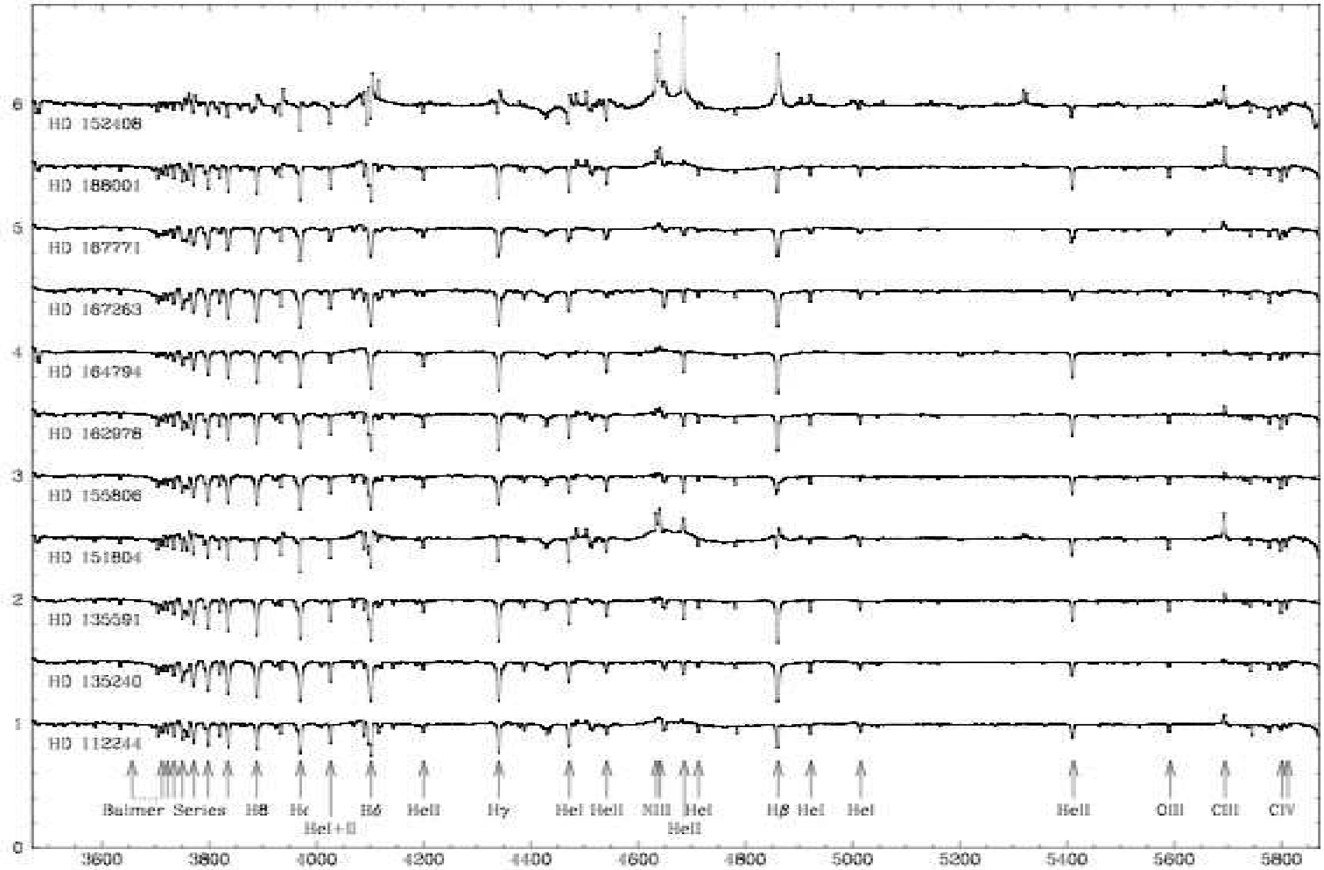

Fig. 1. Normalised FORS 1 Stokes I spectra of O-type stars observed in 2005. Well known spectral lines have been indicated by the arrows, all Balmer lines from the Balmer jump to Hβ are visible. The spectra were offset from 1 by multiples of 0.5 for clarity.

the magnetic field topology with only a few measurements. We would like to emphasize on the other hand that since the existence of magnetic fields in O stars has been suspected for a long time for many compelling reasons, including recent theoretical developments, already a mere discovery of such fields is of great importance, and their subsequent detailed studies will help to explain a wide range of well documented enigmatic phenomena in massive stars.

Normalised FORS 1 Stokes I spectra of all targets observed in 2005 together with the identification of the strongest spectral lines are presented in Fig. 1. Compared to lower mass stars less lines were available for the measurement of the magnetic field and the metal lines are not strong. Even the strongest hydrogen lines have a maximum depth of only about 40% below the continuum, as they are intrinsically weaker than in the B and A type stars. P Cygni profiles and pure emission lines are visible in all stars apart from HD 167263 which shows a weak emission only in the C III line at 5696 Å (only marginally visible at the resolution provided in this paper). This C III line is in emission in the spectra of all studied stars. As we emphasised in the previous section, the lines that show evidence for emission were not used in the determination of the magnetic field strength. Most of these lines are wind-formed and may have very different polarisation signatures.

The results of our magnetic field measurements are presented in Table 3. In the first two columns we give the HD numbers of the targets and the modified Julian dates of the middle of the exposures. The measured mean longitudinal magnetic field $\langle B_z \rangle$ using all absorption lines is presented in column 3. The measured mean longitudinal magnetic field $\langle B_z \rangle$ using all hydrogen lines in absorption is listed in column 4. All quoted errors are 1σ uncertainties. In column 5 we identify new detections by ND. We note that all claimed detections have a significance of at least 3σ, determined from the formal uncertainties we derive. These measurements are indicated in bold face.

Four stars of our sample, HD 36879, HD 148937, HD 152408, and HD 164794, show evidence for the presence of a weak magnetic field in the measurements using all spectral absorption lines. The uncertainties of the mean longitudinal field determination is obtained from the formal uncertainty of the linear regression of V/I versus the quantity $-\frac{g_{\rm eff} e}{4\pi m_e c^2}\lambda^2 \frac{1}{I}\frac{{\rm d}I}{{\rm d}\lambda}\langle B_z\rangle + V_0/I_0$. For measurements obtained from Balmer lines only, the mean uncertainty ranging from 49 to 141 G is generally larger than for measurements using all absorption lines where the uncertainty can be as small as 29 G. These results are easily understandable since the robustness and accuracy of the spectropolarimetric observations increase with the number of spectral lines used for the measurements. In previous studies it was shown that the uncertainty of the FORS 1 measurements can be as low

Table 3. Longitudinal magnetic fields measured with FORS 1 in 13 O-type stars. All quoted errors are 1σ uncertainties.

HD	MJD	$\langle B_z\rangle_{\rm all}$ [G]	$\langle B_z\rangle_{\rm hydr}$ [G]	Comment
36879	54345.389	**180±52**	109±74	ND
112244	53455.193	34±55	15±62	
	53475.177	41±43	1±60	
	53483.104	9±78	−4±79	
135240	53475.246	65±83	86±111	
	53487.263	−37±62	−12±72	
	53553.103	−65±63	−45±78	
135591	53487.243	−118±57	−142±62	
	53553.081	110±54	116±61	
	53571.081	−8±62	−20±71	
148937	54550.416	**−276±88**	−145±104	ND
151804	53476.369	−151±90	−87±96	
	53571.025	68±65	91±73	
	53596.061	82±46	66±48	
152408	53556.216	**−89±29**	−112±57	ND
	53571.104	−91±46	−93±75	
	53596.081	46±34	32±60	
155806	53476.401	−80±132	−216±141	
	53532.283	*−115±37*	*−119±50*	PD
	53532.306	−29±44	−35±70	
	53556.235	−184±88	−160±93	
	54549.403	93±68	54±88	
162978	53556.260	−50±49	−56±86	
	53595.116	91±81	73±84	
	53604.144	80±83	60±89	
164794	53520.357	−114±66	−111±75	
	53594.119	**211±57**	147±72	ND
	53595.096	−165±75	−139±77	
167263	53594.142	−24±91	−54±96	
	53595.015	−19±41	−29±49	
	53596.112	29±53	37±61	
167771	53520.377	5±79	11±85	
	53594.241	92±46	78±73	
	53595.066	−31±54	−16±88	
188001	53520.434	117±65	100±65	
	53594.208	−35±50	−53±55	
	53595.149	−35±36	−32±57	
	53597.149	−95±48	−163±70	

as 13 G in late A spectral types with numerous strong absorption lines (e.g. Kurtz et al. 2008).

The stars HD 36879 and HD 148937 were observed only once and their distinct magnetic field is detected at the 3.5 and 3.1σ level, respectively. Since the rotation period of HD 148937 is known (Nazé et al. 2008), the $v \sin i$ value is relatively low and a comparatively large magnetic field is detected, this star should clearly be of highest priority for future spectropolarimetric observations over the rotation period to study its magnetic field topology. In Table 3 the second observation of HD 152408 reveals a magnetic field at almost 2σ level, and the third observation of HD 164794 shows a magnetic field at 2.2σ level. We should note that the marginal detections of the magnetic field for HD 152408 and HD 164794 on these observing nights can naturally be explained by the strong dependence of the longitudinal magnetic field on the rotational aspect. In case of θ^1 Ori C, out of the ten magnetic field measurements presented by Wade et al. (2006), only four measurements have values larger than 3σ, and among the four measurements of Petit et al. (2008) only one measurement is at a high significance level. Among our 12 observations of θ^1 Ori C, four measurements could be considered as marginal detections. However, all measurements plotted over the rotational phase of 15.4 d can be well–presented by a sine fit characterising a dipole magnetic field of a certain pole strength and inclination to the rotational axis.

Interestingly, most stars in our sample which have been observed on different nights show a change of polarity. The star HD 188001, which was observed on four different nights, shows one 2.3σ detection obtained from Balmer lines and 2σ detection using all absorption lines. The magnetic field of the star HD 135591 was observed at 2.1σ and 2σ levels on two different nights using all absorption lines. Both stars seem to be good candidates for future magnetic field measurements. The star HD 155806 was already observed once with FORS 1 using GRISM 1200g in the framework of the ESO service program 075.D–0507 by Hubrig et al. (2007), who reported the presence of a weak mean longitudinal field, $\langle B_z\rangle = -115\pm37$ G. For convenience the previously published measurement is presented in the same table in italics and marked as PD (previous detection). Four new measurements with the GRISM 600B show a polarity change, but all of them are marginal detections. The first measurement has in addition very low accuracy due to bad weather conditions during service observations. One of the measurements reveals a longitudinal magnetic field at the 2.1σ level: $\langle B_z\rangle = -184\pm88$ G. Although we do not detect magnetic fields for other O-type stars at a 3σ level, it is still possible that some of them host magnetic fields, but that these fields remain undetected due to rather high measurement uncertainties. We note that further observations with an improved accuracy are clearly necessary in order to put an upper limit on the strength of their longitudinal magnetic fields.

Appendix A provides a brief overview of the previous knowledge of the stars with a magnetic field detection at 3σ level. A few notes are also given on HD 155806 for which the presence of a magnetic field was recently reported by Hubrig et al. (2007).

4. Discussion

Stellar magnetic fields have been discovered across a large range of spectral types (see Charbonneau & MacGregor 2001). In late type stars, dynamos active in the convective layers are believed to be the origin of the observed magnetic fields. In earlier type stars, which have radiative envelopes, large scale magnetic fields of the order of a kilogauss have been discovered in Ap/Bp stars, but the exact origin of these fields is not yet known (Charbonneau & MacGregor 2001, Braithwaite & Nordlund 2006). About 10% of main-sequence A and B stars are slowly rotating, chemically peculiar, magnetic Ap and Bp stars and among their descendants, white dwarfs, 10% have high magnetic fields. The magnetic fields in magnetic white dwarfs could be fossil remnants from the main-sequence phase, consistent with magnetic flux conservation (Ferrario & Wickramasinghe 2005). If we assume that massive stars behave like Ap and Bp stars, then for a magnetic field detection probability of 10%, an O stars sample should consist of a larger number of unbiased targets, including stars in clusters and the Galactic field at different ages, in different Galactic metallicity zones, and with different rotational velocities and surface composition. As we mention in Sec. 2, our sample is

biased in the sense that it is restricted to O-type stars exhibiting wind variability, anomalous X-ray behaviour and brightness variations.

Still, this is the first time that magnetic field strengths were determined for such a large sample of stars, with an accuracy comparable to the errors obtained for the three previously known magnetic O-type stars, θ^1 Ori C, HD 155806, and HD 191612. For the magnetic Of?p star HD 191612, Donati et al. (2006a) measured a magnetic field of $\langle B_z \rangle = -220 \pm 38$ G, averaging a total of 52 exposures obtained over 4 different nights. This is similar to our typical errors of a few tens of G. We have found four new magnetic O-type stars which have different spectral types, luminosity classes, and behaviour in various observational domains (see Appendix A). It opens the question whether O-type stars are magnetic in different evolutionary states. The study of the evolutionary state of one of the Galactic Of?p stars, HD 191612, indicates that it is significantly evolved with an ∼O8 giant-like classification (Howarth et al. 2007). The youth of the best studied magnetic O-type star θ^1 Ori C and the older age of the Of?p star HD 191612 suggest that the presence of magnetic fields in O-type stars is not related to their evolutionary state. On the other hand, θ^1 Ori C seems to possess a somewhat stronger magnetic field in comparison to that of HD 191612, indicating that the magnetic field could be a fossil remnant. Considering different size of radii due to the different evolutionary state and assuming conservation of the magnetic surface flux the magnetic field strength is expected to decrease by a factor proportional to the square of the ratio of their radii. Some support for the fossil magnetic field origin arises also from the recent comparative study of magnetic fields of early B-type stars at different ages by Briquet et al. (2007). This work revealed that the strongest magnetic fields appear in the youngest Bp stars, compared to weaker magnetic fields in stars at advanced ages.

It is notable, that the current analyses of Nazé et al. (2008) and Nazé et al. (in preparation) suggest slower rotation than usually observed in O-type stars and nitrogen enhancement in both other Of?p stars, HD 108 and HD 148937. Their multiwavelength studies indicate rotation periods of ∼55 yr for HD 108 and 7 d for HD 148937. Also, recent NLTE abundance analyses of early B-type stars by Morel et al. (2008) and Hunter et al. (2008) confirm that slow rotators often have peculiar chemical enrichments. It is remarkable that the observational data collected by Morel et al. (2008) strongly point to a higher incidence of magnetic fields in stars with nitrogen excess and boron depletion. Clearly, future studies are necessary to determine the efficiency of various indirect indicators for the presence of magnetic fields in the atmospheres of hot stars.

Yet, although it was possible to recognise a few hot magnetic stars as peculiar from their spectral morphology prior to their field detection (Walborn 2006), the presence of a magnetic field can also be expected in stars of other classification categories. Our measurements of 13 O-type stars indicate that magnetic fields are possibly present in stars with very different behaviour in visual, X-ray and radio domains. Subsequent magnetic field measurements will test and constrain the conditions controlling the presence of magnetic fields in hot stars, and the implications of such fields on their mass-loss rate and evolution.

Since no longitudinal magnetic fields stronger than 300 G were detected in our study (apart from θ^1 Ori C) we suggest that large scale, dipole like, magnetic fields with polar field strengths larger than 1 kG are not widespread among O type stars. Stars more massive than about 9 $M_\odot$ end up as neutron stars or as black holes. A significant fraction of newborn neutron stars are strongly magnetized, with typical fields of $\sim 10^{12}$ G, and fields of up to $\sim 10^{15}$ G in the magnetars. Simple conservation of magnetic flux would imply field strengths of at least $(5\,R_\odot/10\ \mathrm{km})^{-2} \times 10^{12}$ G $\simeq 10^1$ G as a minimum for their progenitors. This is similar to the minimum field strength required to explain the wind variability observed in the UV (several 10^1 G), as can be concluded from numerical simulations of wind behaviour in early type stars (ud-Doula & Owocki 2002). Our measurements have a typical accuracy of a few tens of G and it is quite possible that weak magnetic fields are present in the atmospheres of the other stars of our sample, but remain undetected as long as the measurement uncertainties are not significantly improved.

As we mention in Sec. 2, a new mosaic detector with blue optimised E2V chips was implemented in FORS 1 in 2007. To achieve the highest possible signal-to-noise (S/N) ratio – as is required for accurate measurements of stellar magnetic fields – the (200kHz, low, 1×1) readout mode can be used, which makes it possible to achieve a S/N ratio of more than 1000 with only one single sub-exposure. Our recent tests show that using a sequence of 8–10 sub-exposures we can obtain much better accuracies down to 10–20 G. The typical uncertainties presented in Table 2 and 3 at the time of our observations before this CCD upgrade have been of the order of 40 to 70 G.

In the absence of further direct magnetic measurements, it is not clear yet whether more complex, smaller scale fields play a role in the atmospheres of O-type stars. In the case of a more complex magnetic field topology the longitudinal magnetic field integrated over the visible stellar surface will be smaller (or will even cancel) and not be easily detected with the low-resolution FORS 1 measurements, which allow to detect only magnetic fields which possess a large-scale organization. However, high resolution spectropolarimeters should be able to detect such complex field configurations using high signal-to-noise observations of the Zeeman effect in metal lines (e.g. Donati et al. 2006b).

Appendix A: Brief notes on stars with a possible evidence for the presence of a magnetic field

A.1. HD 36879

This star has a classification O7 V(n) according to the Galactic O Star Catalogue (Maíz-Apellániz et al. 2004). It exhibits peculiar narrow emission features in the Si IV line profiles λλ1394, 1403 Å detected by Walborn & Panek (1984a) and Walborn & Panek (1984b). The authors noted that these emission features are strongly variable on the IUE spectra obtained four days apart. Otherwise, this star is only marginally studied, mainly due to its rather fast rotation.

A.2. HD 148937

Only three Galactic Of?p stars are presently known: HD 108, HD 148937, and HD 191612. No attempt has been made yet to measure the magnetic field in HD 108.

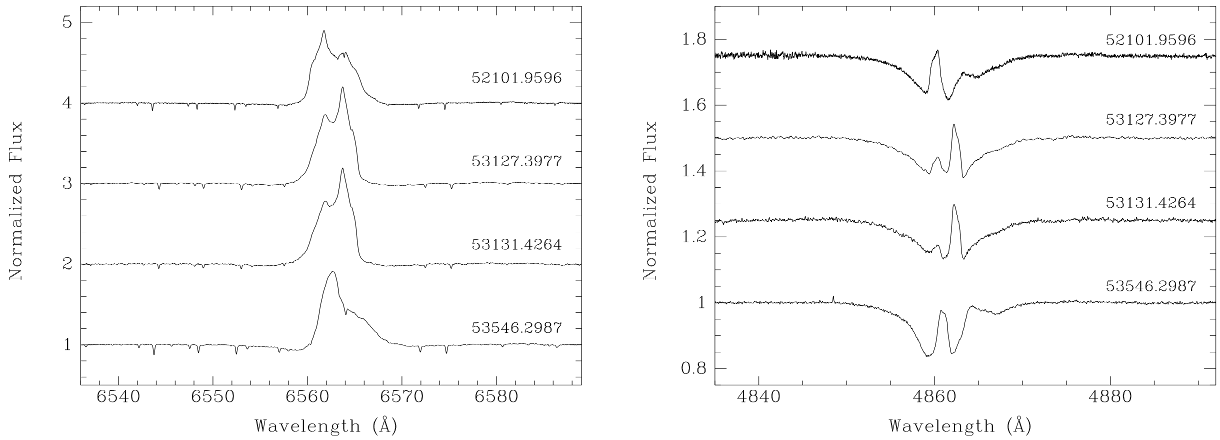

Fig. A.1. Spectral profile variability of the Balmer Hα and Hβ lines in the FEROS and UVES spectra of HD 155806. The spectra are labeled with their modified Julian dates.

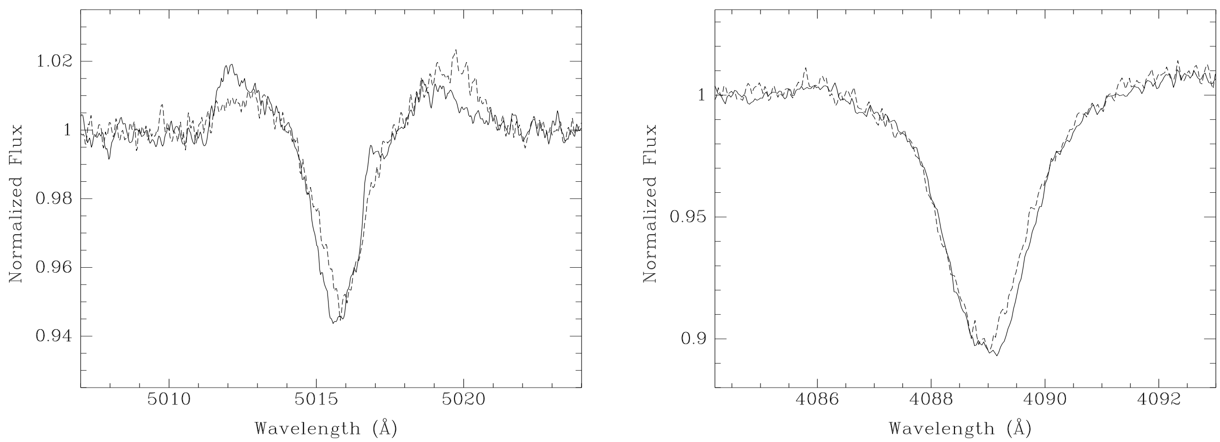

Fig. A.2. Small–scale variations of the He I 5016 Å and Si IV 4089 Å lines in the spectra of HD 155806 obtained on the modified Julian dates 53127.40 (solid line) and 53546.30 (dashed line).

The search for a magnetic field in HD 191612 was motivated by very unusual, large, periodic spectral variations found previously by Walborn et al. (2003) and resulted in $\langle B_z \rangle = -220 \pm 38$ G, measured with ESPaDOnS (Donati et al. 2006a). An extensive multiwavelength study of HD 148937 was recently carried out by Nazé et al. (2008) who detect small-scale variations of He II 4686 and Balmer lines with a period of 7 days and an overabundance of nitrogen by a factor of 4 compared to the Sun.

A.3. HD 152408

This star is a member of NGC 6231 and was classified as O8 Iafpe or WN9ha by Walborn & Fitzpatrick (2000). Observational studies of wind and photospheric variability have been performed by Colley (2003) and Prinja et al. (2001). The interesting fact is that Prinja et al. (2001) discovered that the line profile behaviour was clearly not erratic, but instead organised into sequential localised episodes of enhanced and/or reduced flux, which migrated in velocity as a function of time. They also demonstrated that systematic variability is present in absorption lines formed in the photospheric layers of this star and suggest that the presence of a magnetic field in particular may provide significant variation in the mass-flux and thus also account for the fluctuations discovered in the central regions of the Hα emission line. A medium-resolution spectropolarimetric study of the Hα emission line by Harries et al. (2002) showed that the continuum polarisation agrees well with the local interstellar polarisation pattern. However there appears to be slight evidence of a position angle rotation in combination with a magnitude enhancement across Hα.

A.4. HD 155806

The star HD 155806 has been classified as O7.5 V[n]e by Walborn (1973), but was reclassified by Negueruela et al. (2004) as O7.5 IIIe based on the strength of its metallic features. A strong variability of Balmer lines and small-scale variations of Si IV and He I lines have been detected in FEROS and UVES spectra retrieved from the ESO archive (Programs 073.C–0337, 073.D–0609, 075.D–0061, and 266.D–5655). Spectral profile variations of Hα and Hβ lines are presented in Fig. A.1 and those of the He I 5016 Å and Si IV 4089 Å lines in Fig. A.2.

A.5. HD 164794

This star has a classification O4 V((f)) according to the Galactic O Star Catalogue (Maíz-Apellániz et al. 2004), exhibiting weak N III emission and strong He II λ4686 absorption. It is a well-known non-thermal radio emitter and according to van Loo et al. (2006) the most likely mechanism is synchrotron emission from colliding winds, implying that all O stars with non-thermal radio emission should be members of binary or multiple systems. Hints of a wind-wind interaction were indeed detected in the X-ray domain (Rauw et al. 2002). Currently, a long-term study of its binary nature and spectrum variability is undertaken by our Belgian colleagues (see preliminary results in Rauw et al. 2005).

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